

CLAIMS

I claim:

1. A tool for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said tool having a tool axis and comprising:

a first transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis for transmitting a first transmitted electromagnetic wave into said formation, wherein said first transmitted electromagnetic wave induces a first electric current in said formation, and wherein said first electric current generates a first induced electromagnetic wave in said formation;

a second transmitter antenna spaced apart from said first transmitter antenna along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis for transmitting a second transmitted electromagnetic wave into said formation, wherein said second transmitted electromagnetic wave induces a second electric current in said formation, and wherein said second electric current generates a second induced electromagnetic wave in said formation;

a receiver antenna located between said first and second transmitter antennas along the tool axis and disposed within a plane oriented at a third angle with respect to the tool axis, said third angle being different from said first and second angles, for receiving said first and second induced electromagnetic waves and generating first and second response signals based upon said first and second induced electromagnetic waves, respectively, said first and second response signals being proportional to the electrical resistivity of a portion of said formation; and

a processor in communication with said receiver antenna for (a) receiving said first and second response signals and (b) generating an output signal as a function of borehole depth based on said first and second response signals, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary.

2. The tool of claim 1 wherein said first and second angles are substantially the same.

3. The tool of claim 2 wherein said first and second angles are substantially right angles.

4. The tool of claim 1 wherein said third angle is less than 90 degrees.

5. A tool for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said tool having a tool axis and comprising:

a transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis for transmitting a first electromagnetic wave into said formation, wherein said first electromagnetic wave induces an electric current in said formation and said electric current generates a second electromagnetic wave in said formation;

a first receiver antenna spaced apart from said transmitter antenna at a specified receiver location along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis, said second angle being different from said first angle, for receiving said second electromagnetic wave and generating a first response signal based upon said second electromagnetic wave, said first response signal being proportional to the electrical resistivity of a portion of said formation;

a second receiver antenna spaced apart from said transmitter antenna at said specified receiver location and disposed within a plane oriented at a third angle with respect to the tool axis, said third angle being substantially the negative of said second angle, for receiving said second electromagnetic wave and generating a second response signal based upon said second electromagnetic wave, said second response signal being proportional to the electrical resistivity of a portion of said formation; and

a processor in communication with said first and second receiver antennas for (a) receiving said first and second response signals and (b) generating an output signal as a function of borehole depth based on said first and second response signals, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary.

6. The tool of claim 5 wherein said first angle is substantially a right angle.

7. The tool of claim 6 wherein said second angle is about +45 degrees and said third angle is about -45 degrees.

8. A tool for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said tool having a tool axis and being rotatable about the tool axis, comprising:

a transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis for transmitting a first electromagnetic wave into said formation, wherein said first electromagnetic wave induces an electric current in said formation and said electric current generates a second electromagnetic wave in said formation;

a rotational position indicator for generating an orientation signal representative of the orientation of said tool with respect to a reference direction;

a receiver antenna spaced apart from said transmitter antenna along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis, said second angle being different from said first angle, for receiving said second electromagnetic wave and generating a response signal based upon said second electromagnetic wave, said response signal being proportional to the electrical resistivity of a portion of said formation; and

a processor in communication with said receiver antenna and said rotational position indicator for (a) receiving said response signal and said orientation signal and (b) generating an output signal as a function of borehole depth based on said response signal and said orientation signal, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary.

9. The tool of claim 8 wherein said first angle is substantially a right angle.

10. The tool of claim 8 wherein said second angle is substantially a right angle.

11. The tool of claim 8 wherein said rotational position indicator comprises a gravitational sensor for indicating the orientation of said tool with respect to the direction of the earth's gravity.

12. The tool of claim 8 wherein said rotational position indicator comprises a magnetic sensor for indicating the orientation of said tool with respect to the direction of the earth's magnetic field.

13. A tool for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said tool having a tool axis and comprising:

a first transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis for transmitting a first transmitted electromagnetic wave into said formation, wherein said first transmitted electromagnetic wave induces a first electric current in said formation, and wherein said first electric current generates a first induced electromagnetic wave in said formation;

a second transmitter antenna spaced apart from said first transmitter antenna along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis for transmitting a second transmitted electromagnetic wave into said formation, wherein said second transmitted electromagnetic wave induces a second electric current in said formation, and wherein said second electric current generates a second induced electromagnetic wave in said formation;

a first receiver antenna located at a first receiver location along said tool axis between said first and second transmitter antennas for receiving said first and second induced electromagnetic waves, said first receiver antenna being oriented at a third angle with respect to said tool axis, and said third angle being different from said first and second angles;

a second receiver antenna located at a second receiver location along said tool axis between said first and second transmitter antennas for receiving said first and second induced electromagnetic waves, said second receiver location being different from said first receiver location, said second receiver antenna being oriented at a

fourth angle with respect to said tool axis, and said fourth angle being different from said first and second angles; and

a processor in communication with said first and second receiver antennas;

wherein said first receiver antenna generates a first response signal based on said first induced electromagnetic wave, and said second receiver antenna generates a second response signal based on said first induced electromagnetic wave, said first and second response signals being proportional to the electrical resistivity of a portion of said formation;

wherein said first receiver antenna generates a third response signal based on said second induced electromagnetic wave, and said second receiver antenna generates a fourth response signal based on said second induced electromagnetic wave, said third and fourth response signals being proportional to the electrical resistivity of a portion of said formation; and

wherein said processor receives said first, second, third, and fourth response signals and generates an output signal as a function of borehole depth based on said first, second, third, and fourth response signals, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary.

14. The tool of claim 13 wherein said first and second angles are substantially the same.

15. The tool of claim 13 wherein said first and second angles are substantially right angles.

16. The tool of claim 13 wherein said third and fourth angles are substantially the same.

17. A tool for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said tool having a tool axis and comprising:

a transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis for transmitting a first electromagnetic wave into said formation, wherein said first electromagnetic wave induces an electric current in said formation and said electric current generates a second electromagnetic wave in said formation;

a first receiver antenna spaced apart from said transmitter antenna at a first receiver location along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis, said second angle being different from said first angle, for receiving said second electromagnetic wave and generating a first response signal based upon said second electromagnetic wave, said first response signal being proportional to the electrical resistivity of a portion of said formation;

a second receiver antenna spaced apart from said transmitter antenna at a second receiver location along the tool axis and disposed within a plane oriented at a third angle with respect to the tool axis, said third angle being different from said first angle, for receiving said second electromagnetic wave and generating a second response signal based upon said second electromagnetic wave, said second response signal being proportional to the electrical resistivity of a portion of said formation;

a third receiver antenna spaced apart from said transmitter antenna at said first receiver location along the tool axis and disposed within a plane oriented at a

fourth angle with respect to the tool axis, said fourth angle being different from said first angle, for receiving said second electromagnetic wave and generating a third response signal based upon said second electromagnetic wave, said third response signal being proportional to the electrical resistivity of a portion of said formation;

a fourth receiver antenna spaced apart from said transmitter antenna at said second receiver location along the tool axis and disposed within a plane oriented at a fifth angle with respect to the tool axis, said fifth angle being different from said first angle, for receiving said second electromagnetic wave and generating a fourth response signal based upon said second electromagnetic wave, said fourth response signal being proportional to the electrical resistivity of a portion of said formation; and

a processor in communication with said first, second, third, and fourth receiver antennas for (a) receiving said first, second, third, and fourth response signals and (b) generating an output signal as a function of borehole depth based on said first, second, third, and fourth response signals, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary.

18. The tool of claim 17 wherein said first angle is substantially a right angle.

19. The tool of claim 17 wherein said second and third angles are substantially the same, said fourth angle is substantially the negative of said second angle, and said fifth angle is substantially the negative of said third angle.

20. The tool of claim 19 wherein each of said second and third angles is about +45 degrees and each of said fourth and fifth angles is about -45 degrees.

21. A tool for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said tool having a tool axis and being rotatable about the tool axis, comprising:

a transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis for transmitting a first electromagnetic wave into said formation, wherein said first electromagnetic wave induces an electric current in said formation and said electric current generates a second electromagnetic wave in said formation;

a first receiver antenna spaced apart from said transmitter antenna at a first receiver location along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis, said second angle being different from said first angle, for receiving said second electromagnetic wave and generating a first response signal based upon said second electromagnetic wave, said first response signal being proportional to the electrical resistivity of a portion of said formation;

a second receiver antenna spaced apart from said transmitter antenna at a second receiver location along the tool axis and disposed within a plane oriented at a third angle with respect to the tool axis, said second receiver location being different from said first receiver location and said third angle being different from said first angle, for receiving said second electromagnetic wave and generating a second response signal based upon said second electromagnetic wave, said second response signal being proportional to the electrical resistivity of a portion of said formation;

a rotational position indicator for generating an orientation signal representative of the orientation of said tool with respect to a reference direction; and

a processor in communication with said first and second receiver antennas and said rotational position indicator for (a) receiving said first and second response signals and said orientation signal, and (b) generating an output signal as a function of borehole depth based on said first and second response signals and said orientation signal, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary.

22. The tool of claim 21 wherein said first angle is substantially a right angle.

23. The tool of claim 21 wherein said second and third angles are substantially the same.

24. The tool of claim 23 wherein said second and third angles are substantially right angles.

25. The tool of claim 21 wherein said rotational position indicator comprises a gravitational sensor for indicating the orientation of said tool with respect to the direction of the earth's gravity.

26. The tool of claim 21 wherein said rotational position indicator comprises a magnetic sensor for indicating the orientation of said tool with respect to the direction of the earth's magnetic field.

27. A method for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said drilling apparatus including an electromagnetic propagation logging tool having a tool axis, a first transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis, a second transmitter antenna spaced apart from said first transmitter antenna along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis, a receiver antenna located between said first and second transmitter antennas along the tool axis and disposed within a plane oriented at a third angle with respect to the tool axis, said third angle being different from said first and second angles, and a processor in communication with said first and second transmitter antennas and said receiver antenna, said method comprising the steps of:

(a) transmitting a first transmitted electromagnetic wave into said formation using said first transmitter antenna, wherein said first transmitted electromagnetic wave induces a first electric current in said formation, and wherein said first electric current generates a first induced electromagnetic wave in said formation;

(b) transmitting a second transmitted electromagnetic wave into said formation using said second transmitter antenna, wherein said second transmitted electromagnetic wave induces a second electric current in said formation, and wherein said second electric current generates a second induced electromagnetic wave in said formation;

(c) receiving said first and second induced electromagnetic waves with said receiver antenna thereby generating first and second response signals based upon

said first and second induced electromagnetic waves, respectively, said first and second response signals being proportional to the electrical resistivity of a portion of said formation;

(d) sending said first and second response signals to said processor;

(e) operating said processor to generate a first differential signal based on said first response signal and said first transmitted electromagnetic wave;

(f) operating said processor to generate a second differential signal based on said second response signal and said second transmitted electromagnetic wave;

(g) operating said processor to produce an output signal as a function of borehole depth based on said first and second differential signals, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary; and

(h) controlling the drilling direction of said drilling apparatus in response to said output signal.

28. The method of claim 27 wherein:

said first differential signal comprises the phase difference between said first response signal and said first transmitted electromagnetic wave; and

said second differential signal comprises the phase difference between said second response signal and said second transmitted electromagnetic wave.

29. The method of claim 27 wherein:

said first differential signal comprises the amplitude ratio of said first response signal and said first transmitted electromagnetic wave; and

said second differential signal comprises the amplitude ratio of said second response signal and said second transmitted electromagnetic wave.

30. The method of claim 27 wherein said output signal comprises the difference of said first and second differential signals.

31. The method of claim 27 wherein said output signal comprises the ratio of said first and second differential signals.

32. A method for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said drilling apparatus including an electromagnetic propagation logging tool having a tool axis, a transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis, a first receiver antenna spaced apart from said transmitter antenna at a specified receiver location along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis, said second angle being different from said first angle, a second receiver antenna spaced apart from said transmitter antenna at said specified receiver location and disposed within a plane oriented at a third angle with respect to the tool axis, said third angle being substantially the negative of said second angle, and a processor in communication with said transmitter antenna and said first and second receiver antennas, said method comprising the steps of:

(a) transmitting a first electromagnetic wave into said formation using said transmitter antenna, wherein said first electromagnetic wave induces an electric current in said formation and said electric current generates a second electromagnetic wave in said formation;

(b) receiving said second electromagnetic wave with said first receiver antenna thereby generating a first response signal based upon said second electromagnetic wave, said first response signal being proportional to the electrical resistivity of a portion of said formation;

(c) receiving said second electromagnetic wave with said second receiver antenna thereby generating a second response signal based upon said second

electromagnetic wave, said second response signal being proportional to the electrical resistivity of a portion of said formation;

(d) sending said first and second response signals to said processor;

(e) operating said processor to generate a first differential signal based on said first response signal and said first electromagnetic wave;

(f) operating said processor to generate a second differential signal based on said second response signal and said first electromagnetic wave;

(g) operating said processor to produce an output signal as a function of borehole depth based on said first and second differential signals, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary; and

(h) controlling the drilling direction of said drilling apparatus in response to said output signal.

33. The method of claim 32 wherein:

said first differential signal comprises the phase difference between said first response signal and said first electromagnetic wave; and

said second differential signal comprises the phase difference between said second response signal and said first electromagnetic wave.

34. The method of claim 32 wherein:

said first differential signal comprises the amplitude ratio of said first response signal and said first electromagnetic wave; and

said second differential signal comprises the amplitude ratio of said second response signal and said first electromagnetic wave.

35. The method of claim 32 wherein said output signal comprises the difference of said first and second differential signals.

36. The method of claim 32 wherein said output signal comprises the ratio of said first and second differential signals.

37. A method for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said drilling apparatus including an electromagnetic propagation logging tool having a tool axis, a transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis, a receiver antenna spaced apart from said transmitter antenna along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis, said second angle being different from said first angle, a rotational position indicator attached to said logging tool, and a processor in communication with said transmitter antenna, said receiver antenna, and said rotational position indicator, said method comprising the steps of:

(a) rotating said logging tool about said tool axis as said drilling apparatus drills a borehole in said formation;

(b) using said rotational position indicator to generate an orientation signal representative of the orientation of said tool with respect to a reference direction;

(c) transmitting a first electromagnetic wave into said formation using said transmitter antenna, wherein said first electromagnetic wave induces an electric current in said formation and said electric current generates a second electromagnetic wave in said formation;

(d) receiving said second electromagnetic wave with said receiver antenna thereby generating a response signal based upon said second electromagnetic wave, said response signal being proportional to the electrical resistivity of a portion of said formation;

(e) sending said orientation signal and said response signal to said processor;

(f) using said processor to correlate said response signal with said orientation signal at a first rotational orientation of said tool and a second rotational orientation of said tool;

(g) operating said processor to generate a first differential signal based on said response signal at said first rotational orientation of said tool and said first electromagnetic wave;

(h) operating said processor to generate a second differential signal based on said response signal at said second rotational orientation of said tool and said first electromagnetic wave;

(i) operating said processor to produce an output signal as a function of borehole depth based on said first and second differential signals, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary; and

(j) controlling the drilling direction of said drilling apparatus in response to said output signal.

38. The method of claim 37 wherein:

said first differential signal comprises the phase difference between said response signal at said first rotational orientation of said tool and said first electromagnetic wave; and

said second differential signal comprises the phase difference between said response signal at said second rotational orientation of said tool and said first electromagnetic wave.

39. The method of claim 37 wherein:

said first differential signal comprises the amplitude ratio of said response signal at said first rotational orientation of said tool and said first electromagnetic wave; and

said second differential signal comprises the amplitude ratio of said response signal at said second rotational orientation of said tool and said first electromagnetic wave.

40. The method of claim 37 wherein said output signal comprises the difference of said first and second differential signals.

41. The method of claim 37 wherein said output signal comprises the ratio of said first and second differential signals.

42. A method for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said drilling apparatus including an electromagnetic propagation logging tool having a tool axis; a first transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis; a second transmitter antenna spaced apart from said first transmitter antenna along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis; a first receiver antenna located at a first receiver location along said tool axis between said first and second transmitter antennas, said first receiver antenna being oriented at a third angle with respect to said tool axis, said third angle being different from said first and second angles; a second receiver antenna located at a second receiver location along said tool axis between said first and second transmitter antennas, said second receiver location being different from said first receiver location, said second receiver antenna being oriented at a fourth angle with respect to said tool axis, said fourth angle being different from said first and second angles; and a processor in communication with said first and second transmitter antennas and said first and second receiver antennas; said method comprising the steps of:

(a) transmitting a first transmitted electromagnetic wave into said formation using said first transmitter antenna, wherein said first transmitted electromagnetic wave induces a first electric current in said formation, and wherein said first electric current generates a first induced electromagnetic wave in said formation;

(b) transmitting a second transmitted electromagnetic wave into said formation using said second transmitter antenna, wherein said second transmitted

electromagnetic wave induces a second electric current in said formation, and wherein said second electric current generates a second induced electromagnetic wave in said formation;

(c) receiving said first induced electromagnetic wave with said first receiver antenna thereby generating a first response signal based upon said first induced electromagnetic wave, said first response signal being proportional to the electrical resistivity of a portion of said formation;

(d) receiving said first induced electromagnetic wave with said second receiver antenna thereby generating a second response signal based upon said first induced electromagnetic wave, said second response signal being proportional to the electrical resistivity of a portion of said formation;

(e) receiving said second induced electromagnetic wave with said first receiver antenna thereby generating a third response signal based upon said second induced electromagnetic wave, said third response signal being proportional to the electrical resistivity of a portion of said formation;

(f) receiving said second induced electromagnetic wave with said second receiver antenna thereby generating a fourth response signal based upon said second induced electromagnetic wave, said fourth response signal being proportional to the electrical resistivity of a portion of said formation;

(g) sending said first, second, third, and fourth response signals to said processor;

(h) operating said processor to generate a first differential signal based on said first and second response signals;

(i) operating said processor to generate a second differential signal based on said third and fourth response signals;

(j) operating said processor to generate an output signal as a function of borehole depth based on said first and second differential signals, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary; and

(k) controlling the drilling direction of said drilling apparatus in response to said output signal.

43. The method of claim 42 wherein:

said first differential signal comprises the phase difference between said first and second response signals; and

said second differential signal comprises the phase difference between said third and fourth response signals.

44. The method of claim 42 wherein:

said first differential signal comprises the amplitude ratio of said first and second response signals; and

said second differential signal comprises the amplitude ratio of said third and fourth response signals.

45. The method of claim 42 wherein:

said first differential signal comprises a phase shift resistivity value based on the phase difference between said first and second response signals; and

said second differential signal comprises a phase shift resistivity value based on the phase difference between said third and fourth response signals.

46. The method of claim 42 wherein:

said first differential signal comprises an amplitude attenuation resistivity value based on the amplitude ratio of said first and second response signals; and

said second differential signal comprises an amplitude attenuation resistivity value based on the amplitude ratio of said third and fourth response signals.

47. The method of claim 42 wherein said output signal comprises the difference of said first and second differential signals.

48. The method of claim 42 wherein said output signal comprises the ratio of said first and second differential signals.

49. A method for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said drilling apparatus including an electromagnetic propagation logging tool having a tool axis; a transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis; a first receiver antenna spaced apart from said transmitter antenna at a first receiver location along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis, said second angle being different from said first angle; a second receiver antenna spaced apart from said transmitter antenna at a second receiver location along the tool axis and disposed within a plane oriented at a third angle with respect to the tool axis, said third angle being different from said first angle; a third receiver antenna spaced apart from said transmitter antenna at said first receiver location along the tool axis and disposed within a plane oriented at a fourth angle with respect to the tool axis, said fourth angle being different from said first angle; a fourth receiver antenna spaced apart from said transmitter antenna at said second receiver location along the tool axis and disposed within a plane oriented at a fifth angle with respect to the tool axis, said fifth angle being different from said first angle; and a processor in communication with said transmitter antenna and said first, second, third, and fourth receiver antennas; said method comprising the steps of:

(a) transmitting a first electromagnetic wave into said formation using said transmitter antenna, wherein said first electromagnetic wave induces an electric current in said formation and said electric current generates a second electromagnetic wave in said formation;

(b) receiving said second electromagnetic wave with said first receiver antenna thereby generating a first response signal based upon said second electromagnetic wave, said first response signal being proportional to the electrical resistivity of a portion of said formation;

(c) receiving said second electromagnetic wave with said second receiver antenna thereby generating a second response signal based upon said second electromagnetic wave, said second response signal being proportional to the electrical resistivity of a portion of said formation;

(d) receiving said second electromagnetic wave with said third receiver antenna thereby generating a third response signal based upon said second electromagnetic wave, said third response signal being proportional to the electrical resistivity of a portion of said formation;

(e) receiving said second electromagnetic wave with said fourth receiver antenna thereby generating a fourth response signal based upon said second electromagnetic wave, said fourth response signal being proportional to the electrical resistivity of a portion of said formation;

(f) sending said first, second, third, and fourth response signals to said processor;

(g) operating said processor to generate a first differential signal based on said first and second response signals;

(h) operating said processor to generate a second differential signal based on said third and fourth response signals;

(i) operating said processor to generate an output signal as a function of borehole depth based on said first and second differential signals, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary; and

(j) controlling the drilling direction of said drilling apparatus in response to said output signal.

50. The method of claim 49 wherein:

said first differential signal comprises the phase difference between said first and second response signals; and

said second differential signal comprises the phase difference between said third and fourth response signals.

51. The method of claim 49 wherein:

said first differential signal comprises the amplitude ratio of said first and second response signals; and

said second differential signal comprises the amplitude ratio of said third and fourth response signals.

52. The method of claim 49 wherein:

said first differential signal comprises a phase shift resistivity value based on the phase difference between said first and second response signals; and

said second differential signal comprises a phase shift resistivity value based on the phase difference between said third and fourth response signals.

53. The method of claim 49 wherein:

said first differential signal comprises an amplitude attenuation resistivity value based on the amplitude ratio of said first and second response signals; and

said second differential signal comprises an amplitude attenuation resistivity value based on the amplitude ratio of said third and fourth response signals.

54. The method of claim 49 wherein said output signal comprises the difference of said first and second differential signals.

55. The method of claim 49 wherein said output signal comprises the ratio of said first and second differential signals.

56. A method for steering a downhole drilling apparatus with respect to a geological bed boundary in an earth formation, said drilling apparatus including an electromagnetic propagation logging tool having a tool axis; a transmitter antenna disposed within a plane oriented at a first angle with respect to the tool axis; a first receiver antenna spaced apart from said transmitter antenna at a first receiver location along the tool axis and disposed within a plane oriented at a second angle with respect to the tool axis, said second angle being different from said first angle; a second receiver antenna spaced apart from said transmitter antenna at a second receiver location along the tool axis and disposed within a plane oriented at a third angle with respect to the tool axis, said second receiver location being different from said first receiver location and said third angle being different from said first angle; a rotational position indicator attached to said logging tool; and a processor in communication with transmitter antenna, said first and second receiver antennas, and said rotational position indicator; said method comprising the steps of:

(a) rotating said logging tool about said tool axis as said drilling apparatus drills a borehole in said formation;

(b) using said rotational position indicator to generate an orientation signal representative of the orientation of said tool with respect to a reference direction;

(c) transmitting a first electromagnetic wave into said formation using said transmitter antenna, wherein said first electromagnetic wave induces an electric current in said formation and said electric current generates a second electromagnetic wave in said formation;

(d) receiving said second electromagnetic wave with said first receiver antenna thereby generating a first response signal based upon said second electromagnetic wave, said first response signal being proportional to the electrical resistivity of a portion of said formation;

(e) receiving said second electromagnetic wave with said second receiver antenna thereby generating a second response signal based upon said second electromagnetic wave, said second response signal being proportional to the electrical resistivity of a portion of said formation;

(f) sending said orientation signal and said first and second response signals to said processor;

(g) using said processor to correlate said first and second response signals with said orientation signal at a first rotational orientation of said tool and a second rotational orientation of said tool;

(h) operating said processor to generate a first differential signal based on said first and second response signals at said first rotational orientation of said tool;

(i) operating said processor to generate a second differential signal based on said first and second response signals at said second rotational orientation of said tool;

(j) operating said processor to produce an output signal as a function of borehole depth based on said first and second differential signals, wherein said output signal is indicative of the relative position of said tool with respect to said geological bed boundary as said tool approaches said geological bed boundary; and

(k) controlling the drilling direction of said drilling apparatus in response to said output signal.

57. The method of claim 56 wherein:

said first differential signal comprises the phase difference between said first and second response signals at said first rotational orientation of said tool; and

said second differential signal comprises the phase difference between said first and second response signals at said second rotational orientation of said tool.

58. The method of claim 56 wherein:

said first differential signal comprises the amplitude ratio of said first and second response signals at said first rotational orientation of said tool; and

said second differential signal comprises the amplitude ratio of said first and second response signals at said second rotational orientation of said tool.

59. The method of claim 56 wherein:

said first differential signal comprises a phase shift resistivity value based on the phase difference between said first and second response signals at said first rotational orientation of said tool; and

said second differential signal comprises a phase shift resistivity value based on the phase difference between said first and second response signals at said second rotational orientation of said tool.

60. The method of claim 56 wherein:

said first differential signal comprises an amplitude attenuation resistivity value based on the amplitude ratio of said first and second response signals at said first rotational orientation of said tool; and

said second differential signal comprises an amplitude attenuation resistivity value based on the amplitude ratio of said first and second response signals at said second rotational orientation of said tool.

61. The method of claim 56 wherein said output signal comprises the difference of said first and second differential signals.

62. The method of claim 56 wherein said output signal comprises the ratio of said first and second differential signals.